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BINDING POLYETHYLENE TO POLYPROPYLENE, BY USING DISSIMILAR FRICTION STIR WELDING

*** Sajjad Jalili, * Shayan Jafarian namini, **Hojjat Valipour gharemousa**
****Saein Akrami ouchtapeh, *** Mehdi Zohoor**

** M.Sc., Faculty of Mechanical Engineering,*
**** Associate Professor, Faculty of Mechanical Engineering,*
K. N. Toosi University of Technology, Tehran, Iran

ABSTRACT

The widespread application of thermoplastic polymers in different aspects of industries has motivated researchers and companies to improve and upgrade their forming, joining and assembling processes to overcome their limitations. In this category, friction stir welding (FSW) proposed as an alternative for the traditional joining processes. In this paper, FSW with a threaded cylindrical tool was employed for dissimilar joining of the sheets polyethylene (PE) and polypropylene (PP). In order to control the material flow, the used tool was equipped with a hot shoe. In this paper, the impact of the important process parameters such as tool rotation speed, tool traverse speed and tool tilt angle on mechanical properties of the joint were investigated. The scanning electron microscopy (SEM) was also employed for microstructural observations of the welded samples. By optimizing rotational and traverse speed, enhancement of up to ~116% in joint strength and hardness compared to PE sheet was observed.

Keywords: Thermoplastic polymer, Polyethylene, Polypropylene, Dissimilar welding, friction stir welding

INTRODUCTION

It is necessary to join the same or different plastic products or plastic parts and metals, when the finished assembly is too complex or large, or when different materials must be used in the assembling process [1]. Welding is frequently used for joining thermoplastics, in which the part surfaces are melted, allowing macromolecular chains to diffuse into the opposite specimen at the weld interface [2]. Various welding methods, such as vibration welding [3], laser welding [4], friction welding [5] and friction stir spot welding (FSSW) [6] are known to be effective in different areas of industry. As a novel joining technique, friction stir welding (FSW) is one of the most promising joining methods in the last decade. FSW is capable for joining lightweight alloys that are difficult to weld using conventional techniques. Although some immediate benefits of the technique, such as high-quality finishing of the welded parts and improved resistance to crack propagation relative to the base material are obvious, further focus on the development of the tool is mandatory [7]. FSW has broad application prospect in polymer materials due to the higher weld strength and highly efficient weld seams at energy input [9]. A simple schematic of FSW process is shown in Fig. 1. Thermoplastic materials are now easily joined by FSW. Determination of welding parameters plays an important role in weld strength. In FSW of thermoplastics, traditional tools form a slit on the backside of the welded specimen which leads to root defect and poor tensile strength. Due to the high transparency of thermoplastics, it is possible to easily analyze the morphological changes induced by the welding process [10].

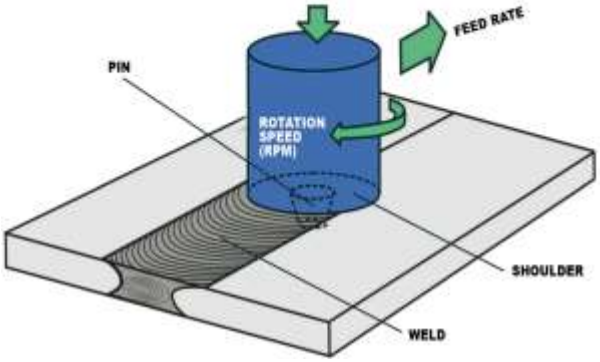


Fig. 1. Schematic view of the FSW process.

FSW process was initially developed for Al-alloys [11–13], but in the period of time, it showed a great potential for the welding of copper [14], titanium [15], steel [16], magnesium [17], metal matrix composites [18] and dissimilar materials [19]. Recently, some researchers have studied the application of FSW on thermoplastic materials [20–22]. Kiss and Czigány [23] employed conventional milling blade friction stir welding process for welding of polypropylene sheets. They examined the effects of process parameters on the joint strength. The maximum joint strength was achieved equal to 50% of base plate. Sadeghian and Besharati [24] studied the mechanical properties of friction stir welding of thermoplastic ABS. Statistical optimization, using response surface methodology, was used to investigate the mechanical strength of the welded samples. Hosein et al. [1] investigated the effect of friction stir welding process parameters on the weld quality and creep properties of welded polyethylene sheets. The results showed that the creep resistance of the welded samples reach to the value of the base material resistance. The stress-strain behavior of the welded joint was also modeled using mathematical methods.

Due to the large application of polyethylene (PE) and polypropylene (PP) thermoplastics in different industries, improving their joining processes has attracted a great attention nowadays. In this paper, the mechanical properties of dissimilar friction stir welded joints of thermoplastic PE and PP are studied through tensile and hardness tests. The scanning electron microscopy (SEM) is also employed for microstructural observations of the welded samples. The effects of main process parameters such as tool rotational speed, tool traverse speed and tool tilt angle on the joint strength are also experimentally studied and discussed.

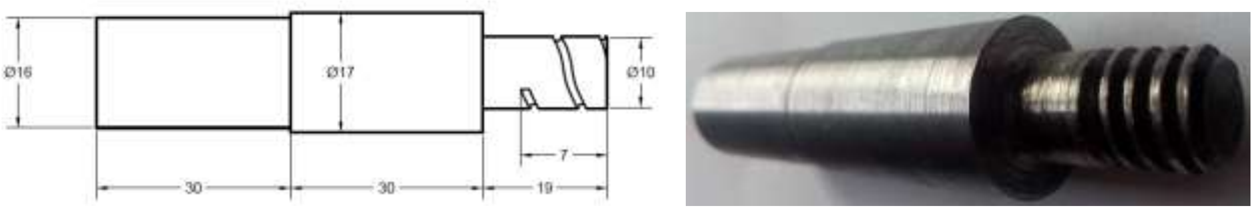
EXPERIMENTAL PROCEDURE

In this study, the PE and the PP sheets were used as the base materials. PE is used in a wide variety of applications. The annual global production of PE is around 80 million tones. The low cost of PE production has encouraged producers to prefer its use over many other plastics. On the other hand, PP has certain advantages such as improved strength, stiffness and higher temperature capability over PE. PE was successfully employed in automotive applications, household goods, containers and packaging [25]. Due to the widespread application of these thermoplastic polymers in different aspects of the industries, the investigation on their dissimilar joining, using friction stir welding, provides valuable insight for further development. A summary of the physical properties of PE and PP is presented in Table 1.

A hot-worked steel tool with threaded shape was used for the welding. The geometry of the tool is shown in Fig. 2 (a). A flat sheet so-called the "hot shoe" along with the welding tool was employed to prevent the outflow of stirred materials, flatten the weld surface and remove the surface imperfections. The schematic view of the hot shoe was shown in Fig. 2 (b).

Table 1. The physical properties of polyethylene and polypropylene polymers.

Material	**Physical state**	**Tensile strength(MPa)**	**Durometer hardness (shore D)**	**Melting temperature (°c)**	**Elongation (%)**	**Density(g/cm^3)**
Polyethylene	**Semi-crystalline thermoplastic**	20.4	60	132	460	0.96
Polypropylene		27	77	170	515	0.855



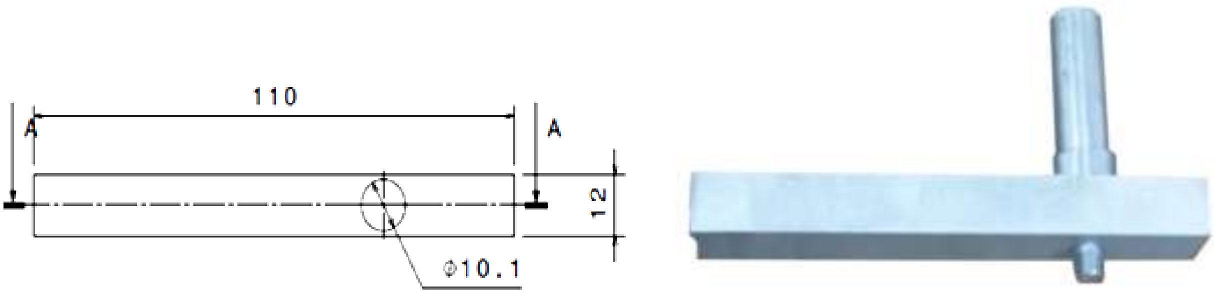


Fig. 2. The Welding tool along with the hot shoe

Rectangular plates of PE and PP sheets with dimensions of 160 × 60 mm^2 and thickness of 8 mm were used in this study. The sheets were fixed in butt position using a purpose-built fixture. All the samples were friction stir welded using an adapted universal milling machine as shown in Fig. 3.

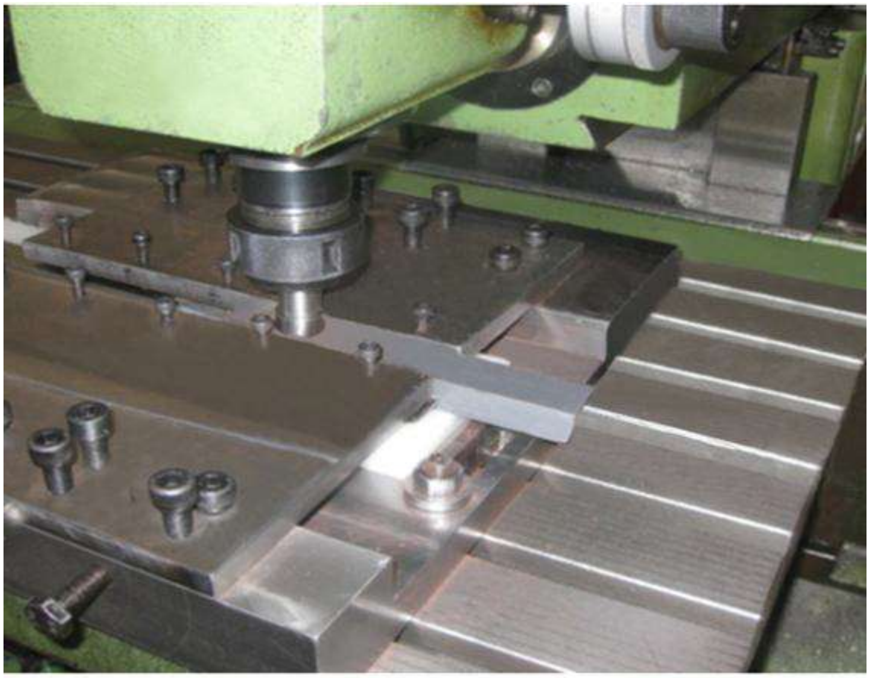


Fig. 3. The positioning of the base material friction stir welding.

In this study, during the friction stir welding of all samples, the tool rotating pin was positioned at the interface of the plates with no offset. The friction stir welding was carried out as follow: firstly, the FSW tool was gradually plunged towards the clamped sheets until the tool shoulder contacts with the hot shoe. This gradual movement of the tool generates sufficient heat, which plasticizes the weld zone. After a period of time, the hot shoe was heated sufficiently and then the traversing of the tool along the joint line was initiated and continued to the end of the weld seam. After a large trial and error experiments (more than 120 experiments), the acceptable ranges of rotational and traverse speed were determined using visual inspection. Three levels for rotational speed and traverse speed were considered for more study, as listed in Table 2.

Table 2. Considered levels for tool rotational and traverse speed

Variable title	**Level 1**	**Level 2**	**Level 3**
Rotational Speed (RPM)	900	1860	2920
Traverse Speed (mm/min)	8	10	12.5

Tensile tests of the samples were performed according to ASTM D 638 using a Santam universal apparatus STM250 at a crosshead speed of 20 mm/min. Standard tensile specimens were extracted from the welded samples using water jet cutting. The geometrical dimensions of the tensile test specimens are shown in Fig. 4.

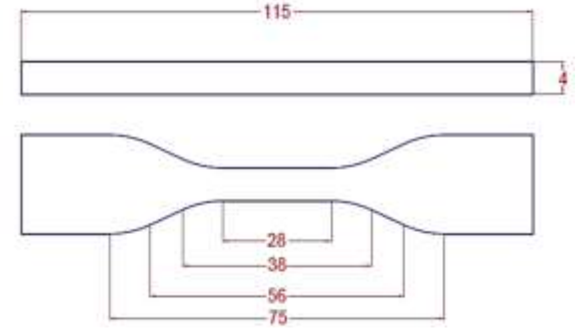


Fig. 4. The geometrical dimensions of the tensile test specimens (in millimeters).

RESULTS AND DISCUSSIONS

It is well known in FSW that the tool rotational and transverse speed rate simultaneously play an indispensable role in heat generation and consequently the quality of the weld joint. To this end, in the present investigation, the effects of the rotational and transverse speeds accompanying the interactions of them on the joint quality were studied.

The results of primary studies revealed that in rotational speeds lower than 900 rpm, no sound joints were achieved due to a lack of generated heat during welding. In some cases, material removal was also observed in the joint line. On the contrary, at the rotational speeds higher than 2920 rpm, melting of base material occurred which caused the material flow out of the weld seam. In these cases, the hot shoe could not also control the melted material. Hence, rotational speeds between 900 rpm to 2920 rpm were considered as the preferable range for the FSW of PE and PP. Melting of base material at traverse speed lower than 8 mm/min and lack of welding heat at traverse speed higher than 12 mm/min led to formation of defective joints. So the optimum ranges for the traverse speed were considered to be between 8 mm/min to 12 mm/min.

TENSILE BEHAVIOR OF THE WELDED JOINTS

In the following, variations of joint strength and elongation of nine welded samples at different rotational and transverse speeds have been studied and discussed using full factorial tests for 3 rotational speeds and 3 traverse speeds. Mechanical properties of the prepared samples are listed in Table 3.

Table 3. Mechanical properties of the dissimilar welded joints of PE-PP.

Traverse speed [mm/min]	**Rotational Speed [rpm]**	**Ultimate Tensile Strength [MPa]**	**Elongation [%]**
8	900	21.3	14.1
10		21.9	14.4
12.5		22.2	14.7
8	1860	21.9	14.8
10		22.1	15.3
12.5		23.7	15.9
8	2920	21.1	13.9
10		21.3	14.1
12.5		21.6	14.3

The maximum tensile strength was obtained for the specimens prepared at tool rotational speed of 1860 rpm and traverse speed of 12.5mm/min which was equal to 23.6 MPa. In Fig. 5, the variation of ultimate tensile strength of the welded joint are presented for different tool rotational and transverse speeds. As can be seen, increasing of the tool rotational speed initially increases the joint strength, while further increase of the rotational rate to 2920 rpm decreases the tensile strength. Increasing the tool rotational speed from 900 rpm to 1860 rpm, generates sufficient heat for better softening and plasticizing of the material around the rotating tool. Whereas, increasing of the tool rotational speed to 2920 rpm causes localized melting of PE, which leads to porosity formation and consequently deterioration of joint mechanical properties.

An increase of traverse speed leads to improvement of tensile strength. It is worth mentioning that Fig. 5 does not depict significant interaction between the tool rotational and transverse speeds.

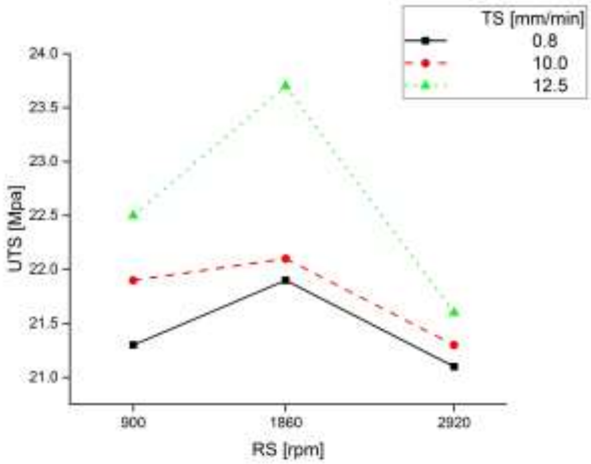


Fig. 5. Interaction plot for joint strength versus the tool rotational speed (RS) and transverse speeds (TS).

The variations of welded joints elongation are also shown in Fig. 6. As it is obvious, the variations of elongation as a function of tool rotational speed and traverse speed follows the same trend as the tensile strength. By increasing the tool rotational speed to 1860 rpm and increasing the traverse speed, elongation of the specimens increased. Similarly, a maximum elongation of 15% above the PE was obtained at tool rotational speed of 1860 rpm and traverse speed of 12.5 mm/min.

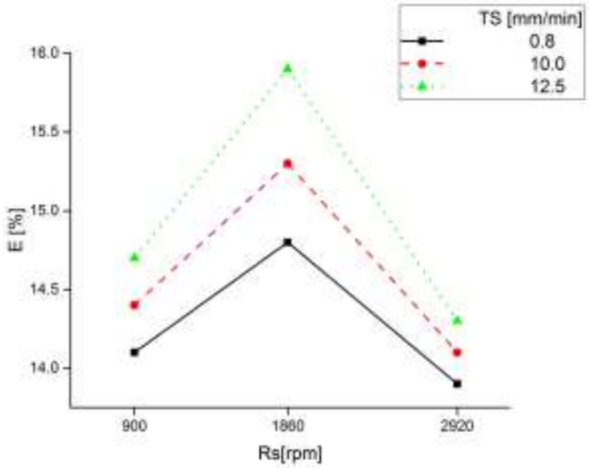


Fig. 6. Interaction plot for elongation versus rotational and traverse speeds.

HARDNESS OF THE WELDED SAMPLES

Hardness is a criterion to estimate the material behavior against plastic deformation. Hardness value can also be utilized for indirect evaluation of mechanical properties. In the current paper, hardness measurement was carried out using shore D hardness scale. Shore hardness is a recommended method for measuring the hardness of rubbers and elastomers [26]. Fig. 7 illustrates the effect of the process parameters on the hardness of the welded samples. Again, the increase in the rotational speed from 900 rpm to 1860 rpm, improves the hardness of the sample due to sufficient heat generation which allows proper material flow and better combination of pasty materials. At the rotational speed of 2920 rpm, extra heat generation, melts the PE plates which are accompanied by more weld defects at the interface. Fig. 7 depicts that applying rotational speed of 1860 rpm and traverse speed of 12.5 mm/min leads to the highest hardness value of 68.6 D which is 17% above the PE hardness and equal to 93% of PP hardness.

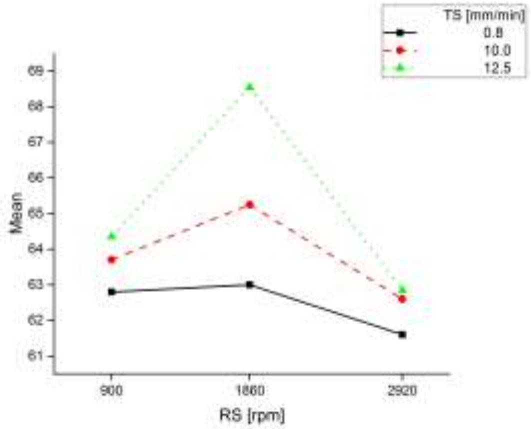


Fig. 7. Interaction plot for hardness versus tool rotational and traverse speeds.

MATERIAL FLOW IN THE WELD ZONE

The tool geometry, especially the existence of hot shoe, plays a critical role in material flow of dissimilar plates of PE and PP. The hot shoe keeps melted materials along the weld seam and prevents sprinkle of materials out of the weld zone. The aforementioned tool geometry helps the production of sound and defect-free welds, which improved the joint mechanical properties. In this section, the material flow behavior of the welded plates was investigated and discussed.

Generally, two typical material flow patterns have been observed in FSW: laminar flow and turbulent flow. For laminar flow, uniform microstructure and sound weld (without defects such as porosity and tunnel) were achieved. On the other hand, for turbulent flow, apparent drop in the mechanical properties of the welded plates was observed due to tunnels remained in the stir zone after welding. Furthermore, the degree of crystallinity shows to decrease in turbulent state.

The tool tilt angle and rotational speed are important parameters which play a dominant role in the material flow in FSW. A suitable tool tilt angle ensures that the stirred materials move efficiently from the front to the back of the pin and return inside the weld zone with the forge pressure of the pin shoulder. The suitable tilt angle varies from 0^{o} to 4^{o} for different materials [27]. Excessive increase of tool tilt angle and consequently pressure in welding resulted in uncontrollable scattering of stirred materials and turbulent flow. High rotational speed also leads to formation of turbulent flow in the stir zone. SEM observations were used to better realize the effect of these two parameters on the material flow pattern.

In order to study the effects of tool tilt angles, 3 specimens with optimum tool rotational speed (1860 rpm) and traverse speed of 8, 10 and 12.5 mm/min and tool tilt angle of 2 degrees are examined. The mechanical properties of these specimens are listed in Table 4.

Table 4. Mechanical properties of the welded samples with tool tilt angle of two degrees.

Traverse speed [mm/min]	**Rotational Speed [rpm]**	**Ultimate Tensile Strength [MPa]**	**Elongation [%]**	**Tool Tilt Angle**
8	1860	20.9	13.8	2°
10		21.2	13.9	
12.5		21.4	14.1	

The comparison between the ultimate tensile strength and elongation of the specimens with different tool tilt angle shows that the ultimate tensile strength and elongation of the specimens were decreased in comparison to the specimens fabricated with no tool tilt angle. This may be attributed to the more welding heat input which extrudes the melted materials at higher tool tilt angle. Fig. 8 and 9 compares the microstructural micrographs of welded samples with tilt angles of 0 and 2°.

Fig. 8. SEM micrograph of microstructure of welded sample with laminar material flow at rotational speed of 1860 rpm and transverse speed of 12.5 mm/min (tilt angle is zero).

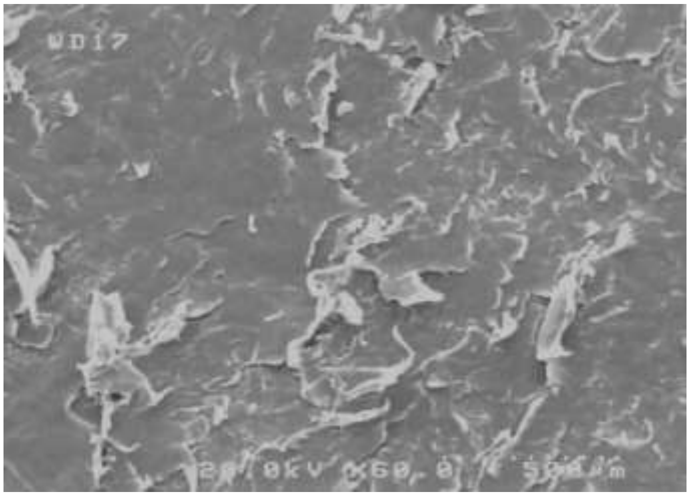


Fig. 9. SEM micrograph of microstructure of welded sample with turbulent material flow at rotational speed of 1860 rpm and transverse speed of 12.5 mm/min (tilt angle is 2 degrees).

A close observation revealed that increasing tilt angle leads to material discontinuity in stir zone which subsequently deteriorate mechanical properties. Fig. 10 shows the generated defects in sample welded by rotational speed of 1860 rpm and transverse speed of 12.5 mm/min.

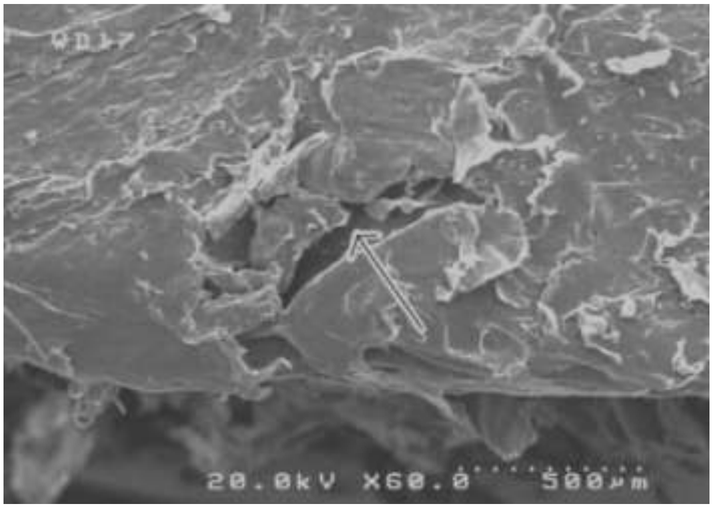


Fig. 10. SEM micrograph of small pores on the cross section of sample welded by rotational speed of 1860 rpm and transverse speed of 12.5 mm/min.

SEM observations revealed that for tilt angle of 0° (Fig. 8), laminar flow is dominant in the respective microstructure. On the contrary, for the sample with the tilt angle of 2° (Fig. 9) a disordered and turbulent microstructure is achieved.

An increase of the tilt angle converts the material flow pattern from laminar to turbulent. The turbulent material flow deteriorates the mechanical properties of the welded joints by producing defects such as hole, porosity and tunnel on the stir zone of these samples.

Fig. 11 illustrates the material flow pattern of the sample welded at rotational speed of 2920 rpm.

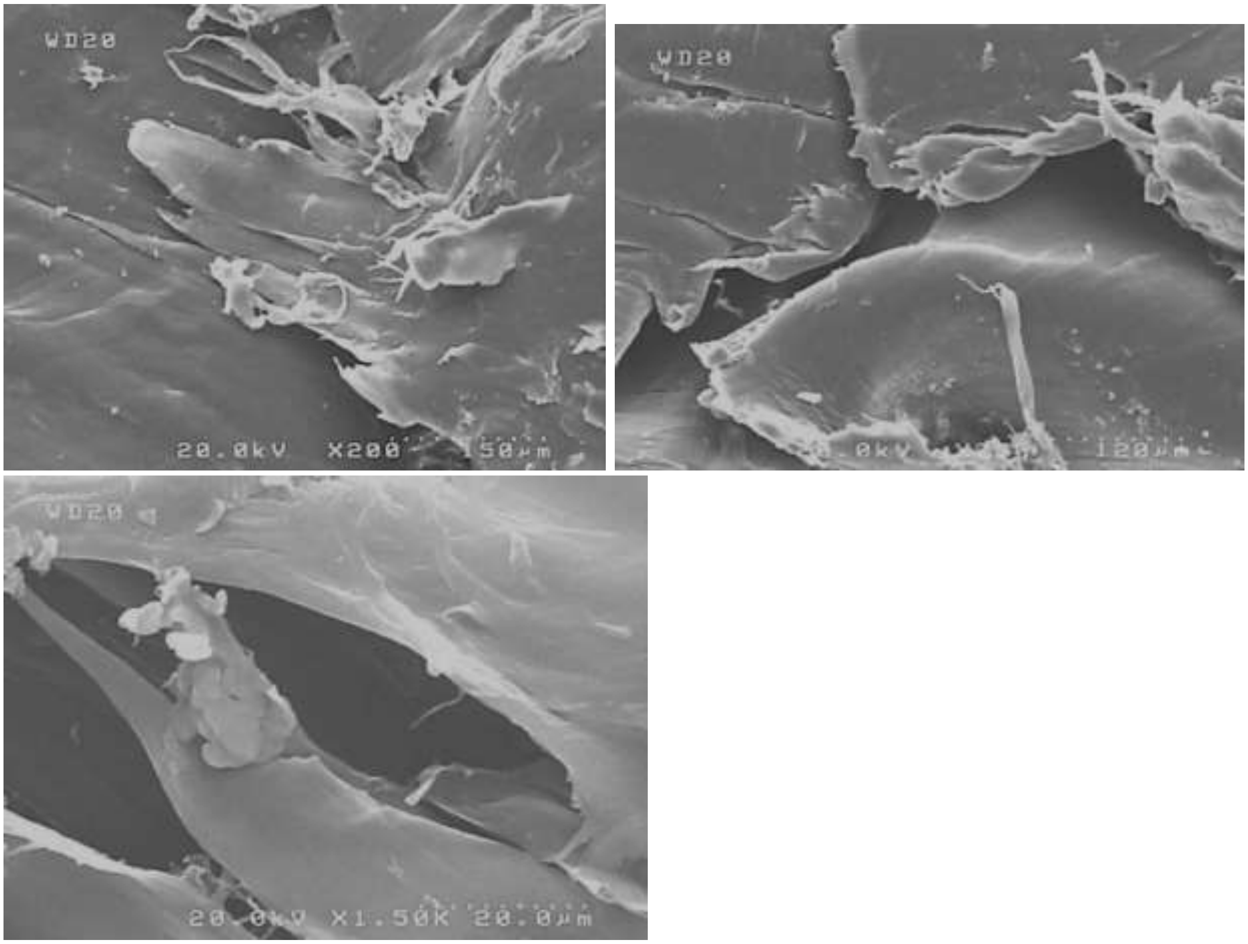


Fig. 11. SEM micrograph of microstructure of welded sample with turbulent material flow at rotational speed of 2920 rpm and transverse speed of 12.5 mm/min.

Increasing rotational speed converted the laminar flow to turbulent. Formation of turbulent flow is the origin of dropping mechanical properties and poor formability of the sample welded by rotational speed of 2920 rpm. Moreover, the turbulent flow can increase the possibility of formation of discontinuity in the respective cross section. Fig. 12 demonstrates the generated tunnel on the sample welded by rotational speed of 2920 rpm.

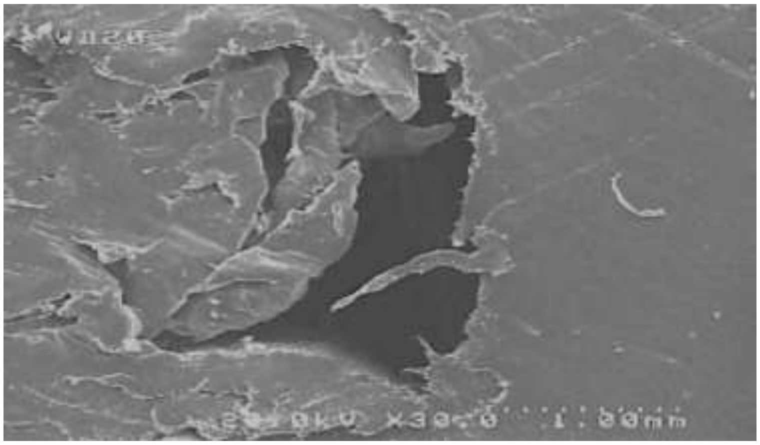


Fig. 12. SEM micrograph of generated tunnel defect on the cross section of sample welded by rotational speed of 2920 rpm and transverse speed of 12.5 mm/min.

Overall, it can be concluded that increasing rotational speed and tilt angle leads to turbulent material flow. The turbulent flow results in elimination of crystallinity, formation of discontinuity and defects in the welded zone. As a result, an obvious drop in the mechanical strength and formability of the joint is observed compared to the base materials.

CONCLUSION

In this paper, FSW of dissimilar thermoplastic polymer sheets of PE and PP on a universal milling machine with a threaded cylindrical tool was investigated. In order to control the material flow during welding, the welding tool was equipped with a hot shoe. Based on the experimental studies, the following important results have been drawn:

- It was observed that with an optimum tool rotational speed and highest tool traverses speed, the highest weld joint strength was achieved. The variation of elongation as a function of tool rotational and traverse speed follow the same trend as the tensile strength.
- Based on the results, with tool rotational speed of 1860 rpm and traverse speed of 12.5 mm/min, the maximum weld strength and elongation about 16% higher than that of the base PE sheet was obtained
- Applying appropriate rotational speed with highest traverse speed resulted in improving the hardness of the weld zone. Accordingly, enhancement of up to 117% in hardness compared to PE sheet was achieved at the rotational and traverse speed of 1860 rpm and 12.5 mm/min, respectively.
- Increasing the tool tilt angle from its vertical position, remarkably decreased the mechanical properties of welded samples. The SEM observations manifested that applying tilt angle converts the material flow regime from laminar to turbulent.

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